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THE ECONOMICS OF USING WIND POWER FOR ELECTRICITY SUPPLY IN THE NETHERLANDS AND FOR WATER SUPPLY ON CURACAO

H. Vermeulen

Translation of "Economische beschouwing over het gebruik van windkracht voor electriciteitsopwekking in Nederland en voor de watervoorziening op Curacao," Koninklijke Luchtvaart Maatschappij, N.V., Report TW 555; GCV-R-128, Wetenschappelijk Bureau, May 19, 1949, 40 pp

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16. Abstract

The present study concludes that it is economically feasible to harness the wind for electricity supply in the Netherlands. The productive power, production costs, etc. of different wind power plants are discussed in detail, with many statistics and tables. Included are an abridged account of a Danish proposal to harness wind power, a calculation of the efficiency of the Danish FLS Aeromotor, and some remarks in connection with Palmer C. Putnam's book Power from the Wind (1948).

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*Indicates a drawing or graph.

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* Indicates a drawing or graph.

THE ECONOMICS OF USING WIND POWER FOR ELECTRICITY SUPPLY IN THE NETHERLANDS AND FOR WATER SUPPLY ON CURACAO

H. Vermeulen

1. Introduction /1*

We were commissioned by the President and General Manager to examine the feasibility of using wind power for water supply on Curacao.

In this connection we held talks with Messrs. L.S. Bouman, Director of the West Indies Authority, W.L. Utermark, General Custodian of the Royal Society Indies Institute, and W. Lulofs, Ex-Director of the Power Authority in Amsterdam.

Once before, during the war, as early as 1941, we were commissioned by the President and General Manager to draw up a preliminary report on the feasibility of generating power economically in the Netherlands by means of wind power stations (Report D 231). In that report, we came to the conclusion that it seemed possible on theoretical grounds to draw from the wind enormous amounts of power for the Netherlands.

That study revealed that the efficiency of about 8 to 10% with which we are familiar from old Dutch windmills can be increased to upwards of 40%; of this, however, we had no practical proof. A test in Russia with a very large mill had delivered an efficiency of only about 25% (Syur) and at 25% it did not seem possible under prewar circumstances, which is what we based our calculations on, to achieve economical production of energy by means of wind power.

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* Numbers in the margin indicate pagination in the foreign text.

Once again we have subjected the different circumstances to close scrutiny, in the course of which Mr. W. Lulofs made available to us a Danish report on tests conducted in Denmark during the war with a very modern wind power station. /2

With this Danish aeromotor, an efficiency of almost 35% was attained. For such a larger station an efficiency of 40% certainly seems attainable. Moreover, the intrinsic value of energy at the present time, as a result of increased coal prices, is so much higher that the generation of energy from wind power now, as compared with the situation in 1940, seems quite justifiable.

What was found by this study is summarized in the following:

2. Conclusions

1. The Danish FLS aeromotor has attained a maximum efficiency of 34.5%. This efficiency already includes mechanical and electrical losses, so that from a much larger wind power station (wheel diameter of 50 m), such as was proposed in Report D 231, just as high an efficiency can surely be expected (see Fig. 4).

2. Calculations showed that the Danish FLS aeromotor with a wheel diameter of 17.5 m would already be economical for the Netherlands to run, even if the cost of construction is higher than the initial expense mentioned with due allowance for the commensurately increased price level in the Danish report.

3. It appears from the calculations of Mr. W. Lulofs (Annex VI) that if use is made of the kWh produced by the wind power station, it will have to be possible to deliver current in the first 20 years at 1.4 ct/kWh and in the last 30 years, at 0.5 ct/kWh, so that the total will be written off in 50 years.

4. At an initial expense that is adjusted to today's money value, the FLS aeromotor appears amply to satisfy what is concluded in Paragraph 3 above and thus can be economically run.

5. Erected in Den Helder at an altitude of 50 m, a wind power station like the one proposed in Report D 231, if "sail is shortened" at 10 m/sec, would be able to reach an annual production of 1,900,000 kWh. If we take advantage of the great amounts of energy that are liberated at higher wind speeds and "shorten sail" only at 15 m/sec, annual production rises to 3,400,000 kWh.

6. If we assume the initial expense per installed kW for a station like the one proposed in D 231 which "shortens sail" at 10 m/sec to be equal to that of the FLS aeromotor, the initial expense of this station becomes f. 311,000. At this price, taking into account Conclusion 3, economical exploitation is possible.

7. If we let such a station "shorten sail" only at 15 m/sec, economical exploitation turns out to be possible to an even greater extent. Even if we take into account an increase in the initial expense due to placing an extra dynamo of 1000 kW and amplification of the station in order to harness the greater powers of higher speeds.

8. It follows from the foregoing that a wind power station could be economically run at the present time as a result of the higher production costs of today's electricity authorities.

9. If wind power could find a wide-spread application in the Netherlands and if wind power plants could be written off in 20 or more years, this would mean an enormous saving in coal and foreign currency, whereas the granting of subsidies to power plants in the form of cheaper fuel deliveries may be entirely or partially suspended. /3

10. It seems desirable to put the above conclusions to the test of the experience that was acquired in Denmark with the FLS aeromotor, and at the same time to get into contact with the University of Copenhagen, which has a school that does research on wind power stations.

11. Should the information from Point 10 support the above conclusion, it would be economically justifiable for the Netherlands to build a pilot plant as soon as possible, which could be ready, at a rough estimate, in 3 years. Allowing 2 years to acquire experience with this plant, we could decide in no more than 5 years whether to build more wind power stations.

12. For the time being, the situation in Curacao is different. The power needs for getting water are local and spread over the island. The well-known small American windmills could be mass-produced there for cheap delivery and could be rapidly erected or moved (see Fig. 6). In spite of their low efficiency, they are satisfactory. On the basis of the results of experiments with a large wind power station in the Netherlands, we could weigh erecting a similar installation on Curacao.

Remark: It should be noted that the greater part of these conclusions is very dependent on construction costs and annual maintenance costs. About this we could make only a very global estimate. It will be possible to carry out more accurate calculations of costs only after the project has been further worked out. If Dutch talks with Denmark take a favorable course, we suggest that a small organizing committee of experts and interested parties be set up for the purpose of making a provisional estimate of the costs involved in such a project.

3. Technical Characteristics of the FLS Aeromotor

On April 23, 1941, Dr. O.V. Mørch lectured to the Danish Engineers' Union on the topic: "Is wind power of real value for the electricity supply of Denmark?" An abridgement of this lecture is reproduced in Annex I.

In the technical part of this lecture, Dr. Mørch shows that the FLS aeromotor signifies an important improvement in the design of wind motors.

From the calculation in Annex II, it turns out that the FLS aeromotor with a wheel diameter of 17.5 m reached a maximum efficiency of 34.5% at a wind speed of 9 m/sec. Electrical and mechanical losses have been included in this efficiency.

The FLS aeromotor is equipped with a 60-kW DC dynamo. That this mill leads to a considerable improvement can be seen from the survey below (see also Annex III).

Efficiency Survey /4

(Theoretical maximum 59.26%)

Old Dutch mills	about 10%
American windmills	about 8% (at low wind speeds)
Old Prince mills	about 10%
New Prince mills	about 12%
La Cour mills	about 20%
Syur mills	about 25%
FLS aeromotor	34.5%

4. Application of Wind Power in the Netherlands

4.1. Productive Power of the FLS Aeromotor

Before taking up the determination of the production costs per kWh, it is first necessary to ascertain what production can be reached in the Netherlands.

Upon our visit to the de Bilt Meteorological Institute, we obtained wind data for Helder and Vlissingen with a correction for wind speeds at an altitude of 50 m (see Annex IV).

On the basis of these data we can plot the so-called wind frequency curves (Fig. 1). This graph shows what percent of the year a certain or higher wind speed occurs.

With the aid of these data and the data concerning the power in kW of the FLS aeromotor at different wind speeds, the annual production can be calculated.

For den Helder, if the mill is erected at an altitude of 50 m, the figures are as follows:

Wind speed	Wind occurrence	Wind occurrence	Delivered power	Production
m/sec	%	hours per year	kW	kWh
< 5	26	2280		
5- 5,9	9	790	5	3950
6- 6,9	8.5	740	12	8880
7- 7,9	9	790	20	15800
8- 8,9	8.5	740	30.5	22570
9- 9,9	7.5	660	42.5	28050
10-10,9	6	530	50	26500
> 10,9	25.5	2230	50	111500
	100	8760		
		Total annual production (rounded off)		220000 kWh.

4.2. Economics of the FLS Aeromotor

In 1941 the FLS aeromotor cost 55,000 Danish crowns. According to Dr. Mørch, this corresponds to a prewar price of 2/3 x 55,000 = 37,000 Danish crowns, or in Dutch money, f. 13,600 (prewar rate 36.365).

Taking into account the depreciation of money, the price under today's conditions thus becomes: 2.69 x f. 13,600 = f. 36,600; per installed kW, this is f. 36,600 ÷ 50 = f. 732.

In comparison with the Danish figures, the prewar amount of maintenance costs and service charges was estimated to be f. 200 per year. Owing to the depreciation of money, under today's conditions, this becomes 2.69 x f. 200 = f. 538 per year, or 0.24 ct. per kWh.

According to Mr. W. Lulofs (Annex VI), it appears that if a use is found for the production of the wind power station, for the first 20 years it will have to be able to deliver current at a price of 1.4 ct. per kWh and for the last 30 years, at a price of 0.5 ct./kWh, if the total writing-off time is 50 years.

It can be calculated from the above (see Annex V-1.1), that the maximum initial expense of the FLS installation could amount to f. 41,100, i.e., f. 821 per installed kW. If we consider that when erecting several FLS aeromotors, one of the 20 is out of service because of repairs and the like, this price becomes 100/105 x f.821 = f. 782 per installed kW.

Inasmuch as the FLS aeromotor per installed kW costs f. 732, there is still a margin of f. 50 per kW, and profitability is ensured.

If we write off the plant normally and again assume that the installed power is 105% of the usable, we get the following production costs for different writing-off times (see Annex V-1.2):

Time of interest and writing-off in years	50	40	30	20	15	10	7	5	2	1
Production costs in ct./kWh	1.01	1.08	1.21	1.49	1,78	2.38	3.12	4.13	9.48	18,34

These figures can be plotted in a curve (Fig. 2).

4.3. Productive power of a Wind Power Plant with a Wheel Diameter of 50 m

Now let us examine the production costs for a wind power plant with a wheel diameter of 50 m erected in den Helder at an altitude of 50 m.

In report D 231 an efficiency of 40% was assumed and, as can be seen from Annex II, it appears that the FLS aeromotor has reached an efficiency of almost 35%. It will therefore be possible for a larger wind power plant to reach a higher efficiency (40%). In our calculations, we assume a mean efficiency of 35%. Now we can calculate the annual production as follows (for a description of the method, see Annex II), where, just like the FLS aeromotor, we let the plant "shorten sail" at 10 m/sec.

V_{wind}	V^3	V^3D^2	N_{th}	N_{pr} ($0.35N_{th}$)	Wind occurrence	Wind occurrence	Production
m/sec			kW	kW	%	Hours per year	kWh
<5					21	1 840	
5	125	312 500	151	53	9	790	42 000
6	216	540 000	260	91	9	790	72 000
7	343	857 500	413	145	9	790	115 000
8	512	1 280 000	617	216	8,5	740	160 000
9	729	1 822 000	878	307	8	700	215 000
10	1 000	2 500 000	1 205	422	7	610	257 000
>10				425	28,5	2 500	1 063 000
					100	8 760	
				Total annual production (rounded off)			1 900 000 kWh

If, however, the plant should "shorten sail" not before a wind speed of 15 m/sec, the annual production would rise by about 1,500,000 kWh (i.e., by about 80%) as can be seen from the following calculation.

V_{wind}	V^3	V^3D^2	N_{th}	N_{pr} ($0.35N_{th}$)	Wind occurrence	Wind occurrence	Production
m/sec			kW	kW	%	Hours per year	kWh
<5					21	1 840	
5	125	312 500	151	53	9	790	42 000
6	216	540 000	260	91	9	790	72 000
7	343	857 000	413	145	9	790	115 000
8	512	1 280 000	617	216	8,5	740	160 000
9	729	1 822 000	878	307	8	700	215 000
10	1 000	2 500 000	1 205	422	7	610	257 000
11	1 331	3 328 000	1 603	561	6	530	297 000
12	1 728	4 320 000	2 082	724	5	440	219 000
13	2 197	5 493 000	2 647	927	4,5	390	362 000
14	2 744	6 860 000	3 307	1 157	3,5	310	359 000
15	3 375	8 428 000	4 067	1 423	3	260	370 000
>15			4 067	1 425	6,5	570	812 000
					100	8 760	
				Total annual production (rounded off)			3 400 000

4.4. Economics of a Wind Power Plant with a Wheel Diameter of 50 m /7

If we assume the same initial expenses per installed kW as for the FLS aeromotor, the total initial expenses of a plant that "shortens sail" at 10 m/sec would be 425 x f. 732 = f. 311,000.

This plant, just like the FLS aeromotor, must be able to deliver current for the first 20 years at 1.4 ct./kWh and for the next 30 years, at 0.5 ct./kWh, while the plant must be written off in 50 years.

Maintenance costs are assumed to be the same as for the FLS aeromotor, i.e., 0.25 ct./kWh. On this basis we can again calculate (see Annex V-2.1.) that the maximum initial expense might amount to f. 355,000, or f. 835 per installed kW.

If we bear in mind that when several plants are used, one out of every 20 plants is regularly out of service because of repairs and the like, this price becomes 100/105 x f. 835 = f. 795 per installed kW.

Inasmuch as the wind power plant costs f. 732 per installed kW, there is still a margin of f. 63 per installed kW, and profitability is ensured.

If, however, the wind power plant "shortens sail" not before 15 m/sec, production (see 4.3.) can rise from 1,900,000 kWh to 3,400,000 kWh. To this end, for example, a 425-kW dynamo can be used, while if the wind strength increases above 10 m/sec, a change is made over to a 1000-kW dynamo, and if its power is still not enough (at about 13 m/sec), both could be switched in. Because of the lower commercial value with this increase in production, current could no longer be sold at 1.4 ct./kWh but only at 1.1 ct./kWh (see Annex VI).

At similar maintenance costs per kWh as for the FLS aeromotor, we can again calculate (cf. Annex V-2.21.) that the increase in the initial expense because of amplification of the plant could at most amount to f. 206,000, i.e., about 57% of the original initial expense.

Thus, the total initial expense would be at most f. 355,000 + + f. 206,000 = f. 561,000 if we take into account the fact that the installed power is 105% of the usable, the maximum initial expense could come to f. 534,000.

Thus, this increase would be the natural result of amplifying the plant in order to harness the greater powers of stronger winds, as well as of the larger dynamo that it would especially pay off to install.

The increase in initial expenses due to this improvement, however, would surely not amount to 57% but to less, so that a wind power station that "shortens sail" not before 15 m/sec would be more economical to run.

If we write off normally the above-mentioned plant in 50 years or less, then, for a plant that "shortens sail" at 10 m/sec, we must start from an initial expense of f. 311,000, and for a plant that "shortens sail" not before a wind speed of 15 m/sec is reached, an initial expense of f. 470,000 (assuming that the amplification of the plant costs 50% of the original initial expenses). If we again take into account the fact that one of the 20 wind power plants that are in use is continually out of service because of repairs and the like, then calculation (see Annex V-2.3.) yields the following production costs for different writing-off times:

a. For an annual production of 1,900,000 kWh (at 10 m/sec): /8

Time of interest and writing-off in years	50	40	30	20	15	10	7	5	2	1
Production cost in ct/kWh	1.00	1.07	1.20	1.47	1.76	2.33	3.07	4.07	9.31	18.05

It can be seen from the above that if we can get 1.4 ct/kWh for the first 20 years, the plant is already almost written off in those 20 years.

b. For an annual production of 3,400,000 kWh (at 15 m/sec):

Time of interest and writing-off in years	50	40	30	20	15	10	7	5	2	1
Production cost in ct/kWh	0.88	0.94	1.05	1.30	1.52	2.01	2.64	3.48	7.90	15.29

If we calculate that current can be sold for the first 20 years at an average of $\frac{1.1 \times 1.5 + 1.4 \times 1.9}{1.5 + 1.9} = 1.27$ ct/kWh (see p. 10), it appears that this plant, too, is already almost written off in the first 20 years.

Thus, the greater power of the latter plant gives it an advantage over the plant with the smaller power inasmuch as both can be written off in about the same period.

The figures from a. and b. can again be plotted as a curve (see Fig. 3).

4.5. Reflections on the FLS Aeromotor and a Wind Power Plant with a Wheel Diameter of 50 m

The above calculations clearly show that wind power can be economically exploited, the more so as the kWh prices that we ~~start from are pessimistic with regard to wind power.~~ As far as today's high fuel prices are concerned, in view of today's fuel and money scarcity, no drop in coal prices is certainly to be expected. These facts, too, plead in favor of using wind power. In other countries, too, attempts are being made to draw energy from the wind with a high efficiency, witness among others, the Danish experiment mentioned in the present report and the fact that Great Britain recently set up a committee to study to what extent wind power can be used for energy supply.

As far as electricity supply in the Netherlands by means of atomic energy is concerned, we believe that wind power stations can already be written off to such an extent (see Fig. 3) that they will be able to compete with all other methods of generating current that are appropriate for the Netherlands.

This opinion can be explained as follows. There is indeed room for the question whether it is still justifiable to invest a great deal of capital in the development of new energy sources in view of the possibility of liberating great amounts of energy -- for industrial purposes, too -- that nuclear physics has opened up through nuclear fission of the heaviest elements. For /9 it is an established fact that from 1 kg of uranium as much energy can be liberated as from 2000 tons of coal. It is of interest to put this much-discussed possibility in the proper perspective with a few remarks.

In the first place, the difficulties that have yet to be surmounted before this energy source can be useful for general application in practice are still very considerable, witness the pronouncement of M.H.L. Price that appeared in the Bulletin of Atomic Scientists, 1948. In this article, he expresses the opinion that it will be more than 30 years before nuclear energy will begin to catch up with coal energy. In the second place, opinions as to the production costs to be expected differ widely. According to the view prevailing in America, the birthplace of the use of atomic energy, investment costs per kW may amount to about 2.3 times those for coal power plants, while a publication with reference to the Netherlands speaks of similar capital costs.[1] But even on this assumption, the production costs calculated for 20,000 and 100,000 kW become respectively 3 ct and 2 ct per kWh for a coal power plant and 2.9 ct and 1.8 ct for a nuclear power plant.

In the third place, unlike wind power, which is inexhaustible, the extraction of energy from nuclear fission cannot yet be regarded as a definitive solution for the future because of the relatively small quantities of available high-grade ore. Thus, in the USA, the energy source from exploitable coal is about 180 times greater than that from atomic energy from nuclear fission of available high-grade ores.

Of course, there is a superabundance of low-grade uranium and thorium ores in the earth, but about the possibility of using these sources, too, in a technologically and economically satisfactory manner, no prediction can yet be made.

We have yet to consider that the Netherlands possesses no such ores (although thorium can be encountered in the Netherlands Indies) and that her coal stock is relatively small, whereas wind energy is plentiful.

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[1] See Science, (Nov. 1948) and Ned. T. Natuurk. 16, (Feb-March 1948).

Finally, let us summarize the advantages of a wind power station with a wheel diameter of 50 m:

1. The plant delivers good amounts of energy, so that it can be directly connected into the high-voltage network.

2. The plant has a high efficiency (about 40%, i.e., about 67.5% of the theoretical maximum efficiency).

3. The service life of the plant is very great. Except for repairs to the sails and the electromechanical part, the plant can last an unlimited time.

4. The servicing of the plant can be completely automated and centrally controlled, so that supervision can be confined to a minimum.

In Annex VI, Mr. Lulofs discusses the economics of using wind energy in the Netherlands and points out some important and interesting facts.

Thanks to the valued collaboration of Mr. Lulofs, it was possible to treat the electrotechnical and economic problems on a more realistic basis.

5. Application of Wind Power on Curacao /10

Now let us consider the situation on the island of Curacao. According to data furnished by Mr. Bouman, Director of the West Indies Authority, at the present time there are about 3000 American windmills in use on Curacao which, depending on the condition of the wells they work with, the depth of these wells, and the dimensions of the mills, produce 5-24 tons of water per day.

The advantages of the American windmills can be summarized as follows:

1. The motor is very cheap because it is mass-produced and can be directly delivered on the spot.

2. The mill can deliver its small power directly to the place where it is deemed necessary.

3. The mill already produces at low wind speeds.

As disadvantages we can mention:

1. the low yield (about 8%);

2. the unusability of the mill at high wind speeds.

The powers necessary for irrigation and drinking water supply are small and local, so that if we look at the matter from the standpoint of economics as well as of the above-mentioned advantages and disadvantages, it seems to us more advantageous -- at least for the time being -- to use the American windmills than wind power plants.

Moreover, the electric power plants on Curacao can produce current pretty cheaply since they burn mainly asphalt for fuel, which is more or less a byproduct of the oil refineries.

Except in Russia, no large wind power plants have yet been built, so that initial expenses will at first be higher than for American windmills. But we see no reason why the price per pkh should be higher in the long run than that of the American windmills. If, therefore, the Netherlands should switch over to investing in large wind power plants, we would be able, with the aid of the experience acquired in the Netherlands, to switch over to building similar plants in Curacao.

If we should already wish to generate electricity on Curacao by means of wind power, we might examine to what extent a smaller wind power plant of the FLS type would be economic to run in those places where the power that the American windmill delivers is too low.

Wind frequency

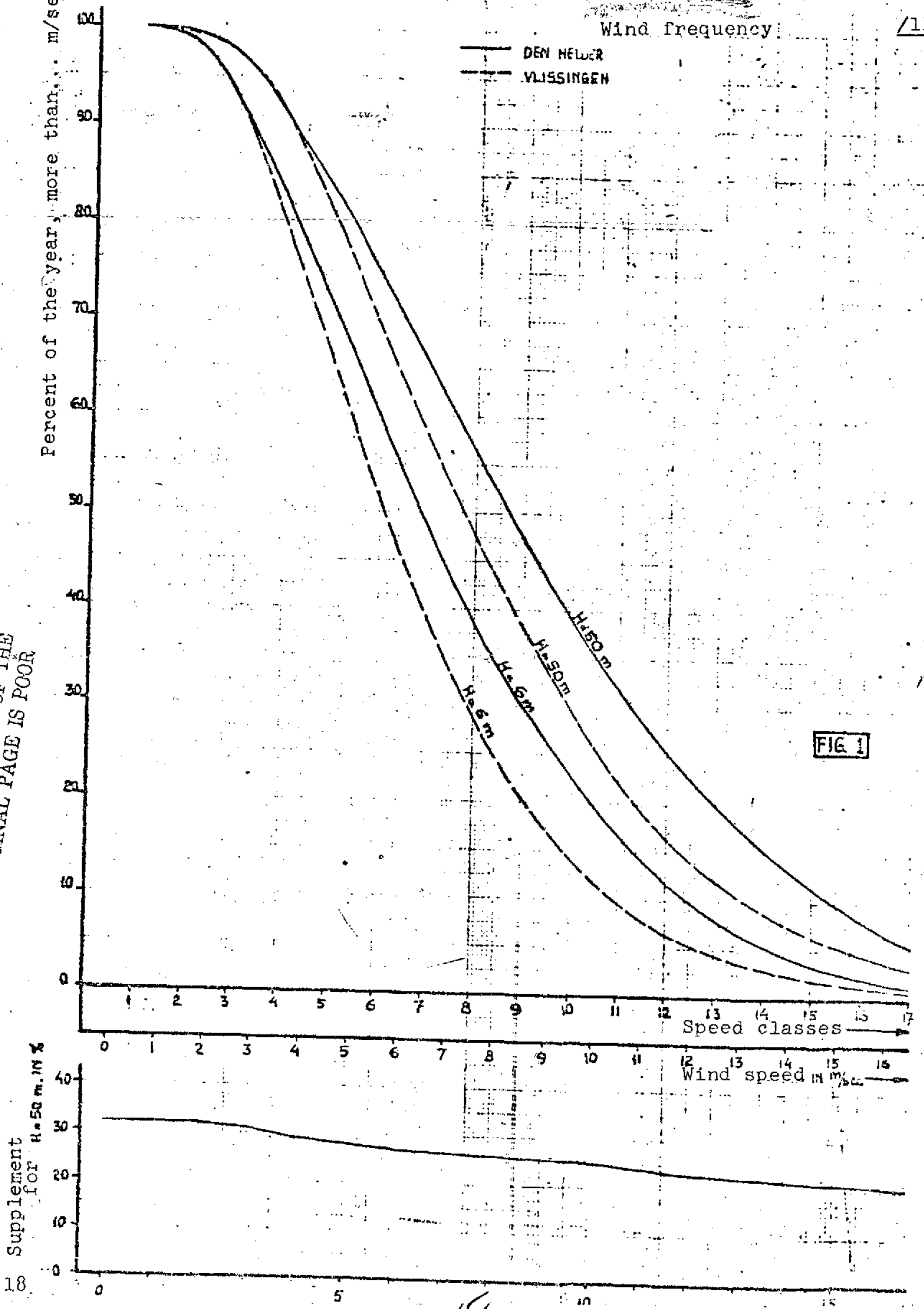


FIG 1

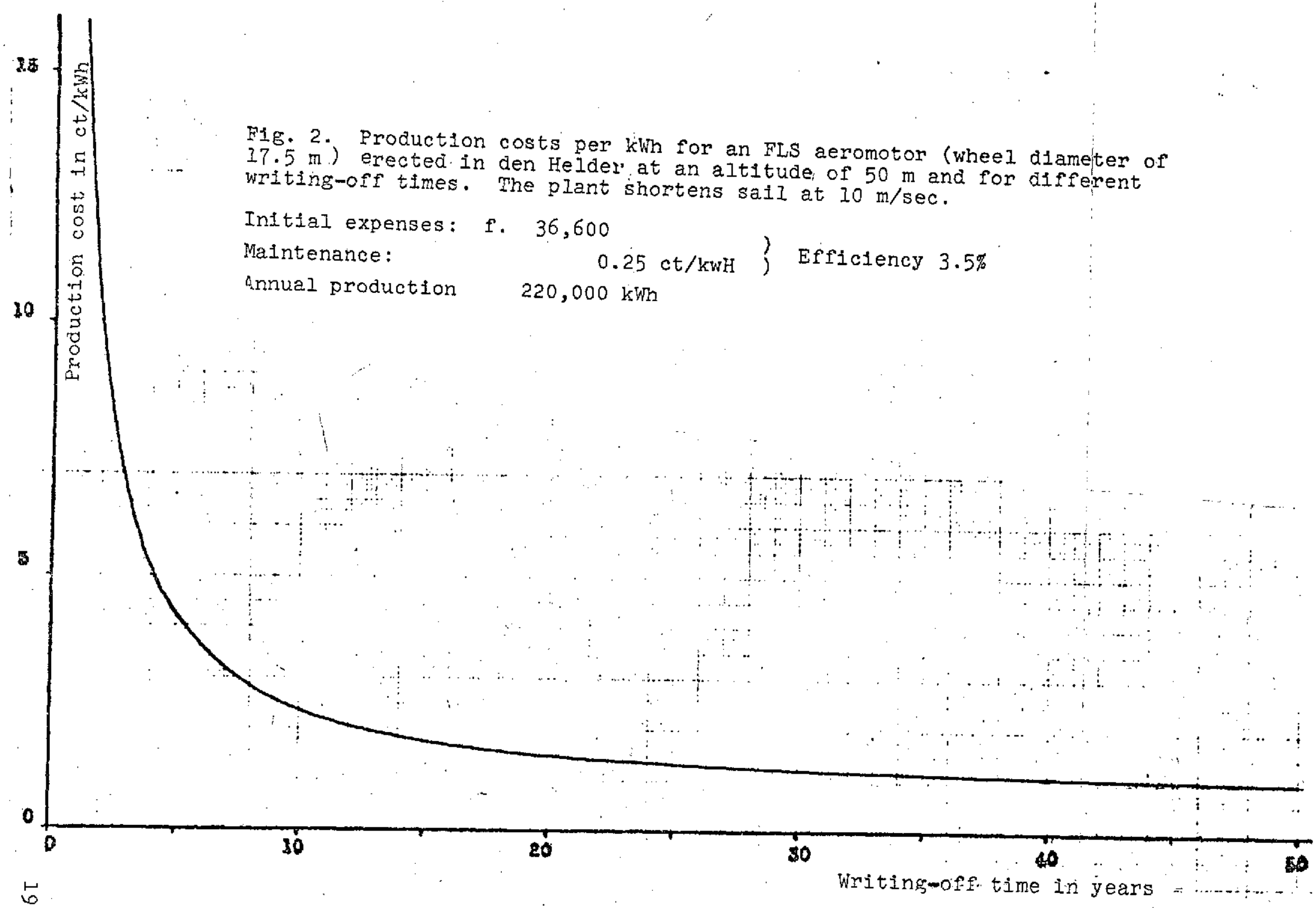


Fig. 2. Production costs per kWh for an FLS aeromotor (wheel diameter of 17.5 m) erected in den Helder at an altitude of 50 m and for different writing-off times. The plant shortens sail at 10 m/sec.

Initial expenses: f. 36,600

Maintenance: 0.25 ct/kwH } Efficiency 3.5%

Annual production 220,000 kWh

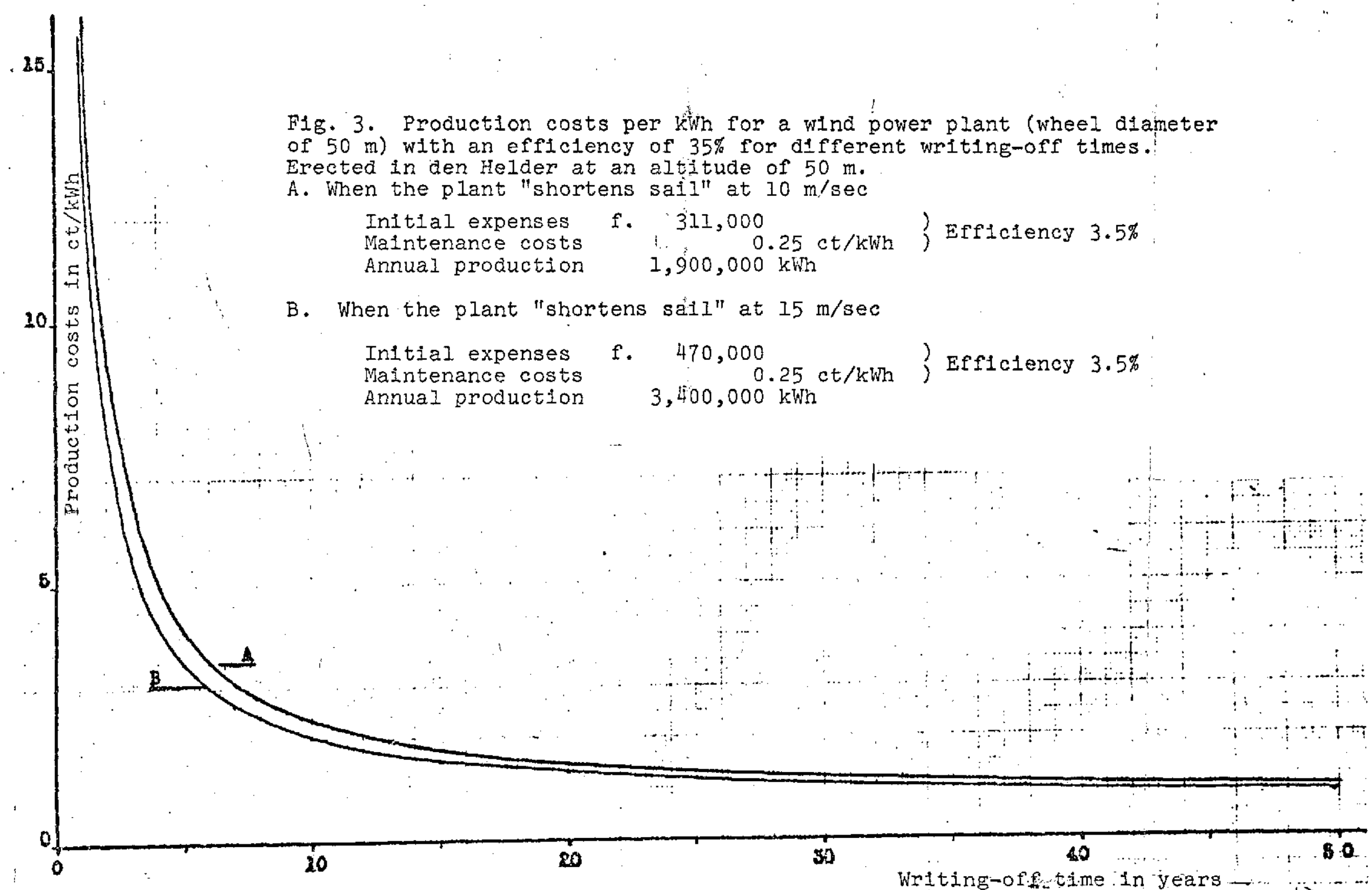


Fig. 3. Production costs per kWh for a wind power plant (wheel diameter of 50 m) with an efficiency of 35% for different writing-off times. Erected in den Helder at an altitude of 50 m.

A. When the plant "shortens sail" at 10 m/sec

Initial expenses	f. 311,000		Efficiency 3.5%
Maintenance costs		0.25 ct/kWh	
Annual production	1,900,000 kWh		

B. When the plant "shortens sail" at 15 m/sec

Initial expenses	f. 470,000		Efficiency 3.5%
Maintenance costs		0.25 ct/kWh	
Annual production	3,400,000 kWh		

Large Wind Power Plant with Four Sails

/15A

The wind power plants discussed in the present report are assumed to be equipped with two sails. In today's aircraft technology, more and more use is being made of three- and four-bladed high-activity propellers, which are more efficient. In this connection, wind power plants can also be equipped with four sails, whereby a higher efficiency could be obtained and a greater conformity of esthetic forms with the well-known Dutch windmills.

A sketch of such a plant can be found on the following page.

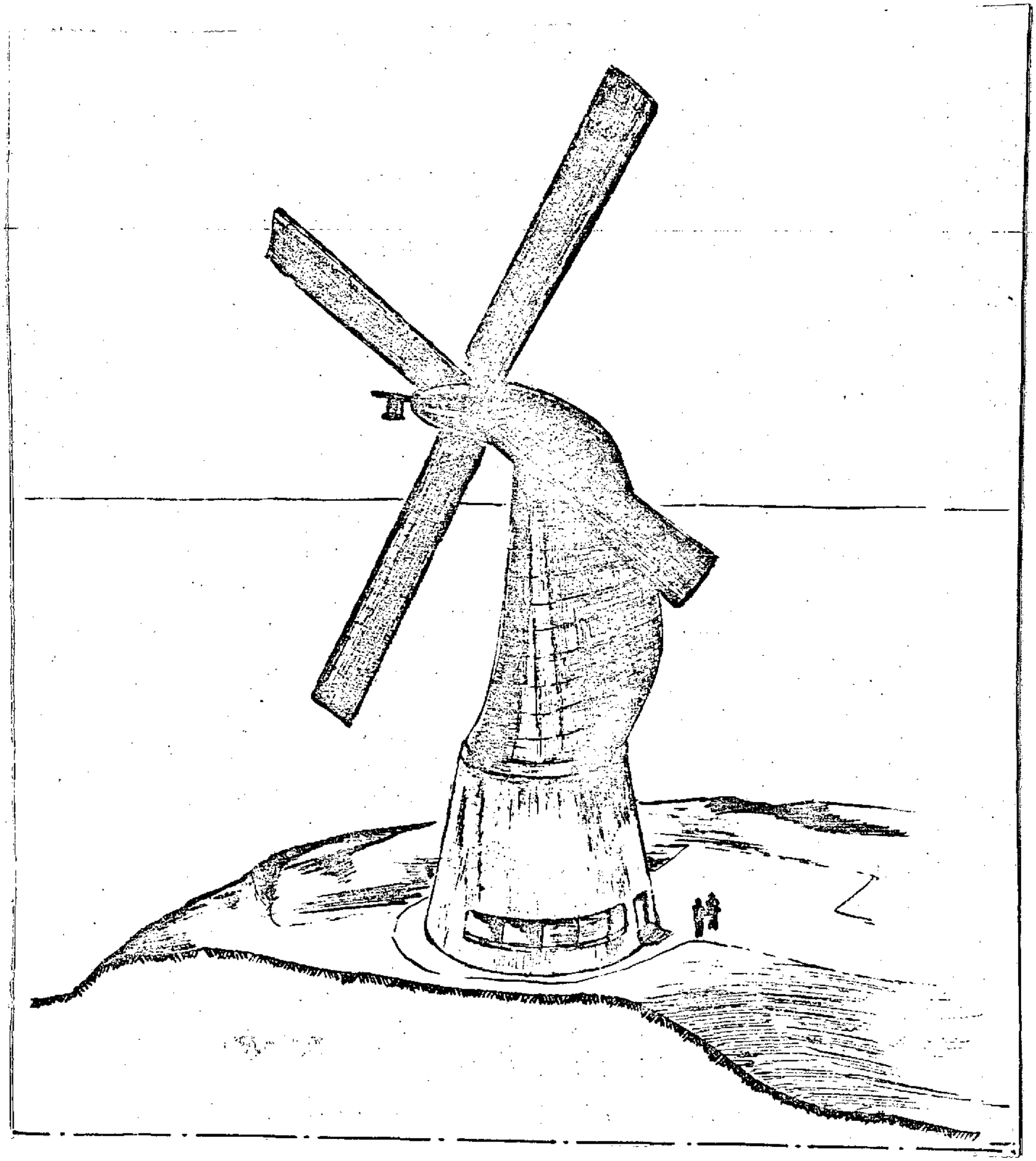


Fig. 4. Wind power plant with four sails. Wheel diameter 50 m. KLM proposal.

ANNEX I. Is Wind Power of Real Value for Electricity Supply in Denmark? /1

What follows is an abridged account of a lecture delivered to the Danish Engineers' Association on April 23, 1941 by Assistant Manager D.V. Mørch, association member and civil engineer, on a visit to the mechanical engineers' group.

1. Technological Development

A good deal of work is being carried on in Denmark to develop windmills. A well-known name in this field is that of La Cour, who created the first practically working wind-driven electricity power plant (Askov).

At that time, La Cour's "sail clapper" constituted a great advance. Toward the end of the First World War, a more rational type of mill appeared, namely, Dr. Vinding's Agricomill. Its sails are built in accordance with experience acquired with aircraft wings. A great number of these mills were built in Denmark as well as abroad, and they yielded good results.

Dr. Vinding worked together with Chief Engineer Johannes Jensen, and they tried to use the mills to generate alternating current. An asynchronous generator was used which was connected into the network only when it had reached a supersynchronous speed. At the same time, Johannes Jensen suggested how an AC commutator machine could be rigged up to produce an effect incident to the sharply varying speeds of the wind motor.

Prof. Absalon Larsen proposed in De Engenieur letting the wind motor draw a shunt dynamo whose current drives a series motor which is then recoupled with a synchronous AC generator. This will then run at constant rpm and the delivered effect will then be directly proportional to the moment of revolution to which this generator is subject. This eliminates the effect of the uneven running of the wind motor. The outbreak of war in 1939 had the result that a pretty large number of windmills were built for smaller rural electricity plants, including several with pretty large mills with a wheel diameter of 12 to 18 m. There are now probably about [illegible] electricity plants that use these "sail clappers" and, moreover, a number of these mills are still being built. These mills drive DC dynamos with a maximum of 30 kW. Statistics in this connection published by the Board of Directors of the Rural Electricity Authority in Denmark are shown in Table 1.

Thus, as these statistics show, the total production in 39 of /2
these plants in January 1941 amounted to about 108,000 kWh. Now January was a still month of frosty weather, i.e., a bad month for winds, so that, if all plants equipped with a mill are taken into account, we can easily count on a monthly production of 150,000 kWh and an annual production of 1,800,00 kWh.

Another type of wind motor with streamlined propeller blades appeared last year at the initiative of Dr. Gunnar Larsen before he assumed the duties of Minister of Public Works. The plans were worked out by the electrical department of F.L. Smidt & Co. under the leadership of Dr. Claudi Westh and in collaboration with Dr. Zeuthen, a Scandinavian aviation industrialist. The result was a new wind motor that is being manufactured under the name of FLS aeromotor.

A pilot mill with 17.5-m-long blades was erected on ground belonging to the "Danmark" cement plant in Aalborg.

The vanes of this mill are built in accordance with the laws /3
of aerodynamics. The blades are fixed -- not rotatable like those of the Agricomill, for example -- and "sail shortening" is brought

TABLE 1. WIND ELECTRICITY STATISTICS FOR THE MONTH OF JANUARY 1941

Name of the electricity authority	Sail length in m	Generated in Jan.	Highest prod. Date	24 hours in Jan. kWh	Total generated in '41
Askov pr. Vejen	18	4058	21/1	510	4058
Besser Samsø	18	5995	21/1	462	5995
Bregninge pr. Aerøskøbing	18	2075	31/1	183	2075
Baekmarksbro	18	2572	28/1	238	2572
Bøvling pr. Bøvlingbjerg	18	2739	16/1	400	2739
Dalby	16	684	21/1	139	684
Faster	18	4803	31/1	508	4803
Femø	18				
Finderup pr. Herborg	18	981	21/1	156	981
Forsum pr. Tarm	14	1400	28/1	300	1400
Gjelsted	18	1980	30/1	231	1980
Herritslev pr. Nysted	18	2241	21/1	275	2241
Horne pr. Tistrup	18	2973	30/1	300	2973
Hvidberg	18	2664	21/1	347	2664
Hvide Sande	?	800			800
Højmark pr. Lem	18	4371	21/1	378	4371
Jernved pr. Gredstedbro	18	3215	22/1	442	3215
Kappendrup	18	4224	22/1	510	4224
Kvaerndrup	18	3500	21/1	505	3500
Kølstrup	19	4154	21/1	436	4154
Lem	14	1083	29/1	191	1083
Lunde (Jylland)	14	2623	21/1	273	2623
Lunde (Fyn)	18	2010	21/1	347	2010
Lomborg pr. Bonnet	18	5520	22/1	446	5520
Marslev	18	2242	21/1	270	2242
Ørager	18				
Røding	18	00			00
Rolfsted	18	2941	21/1	350	2941
Roerslev pr. Kappendrup	18	5099	31/1	415	5099
Slemminge	18	2200	22/1	271	2200
Staaby	16	1181	21/1	351	1181
Skamby	18	3870	31/1	518	3870
Strijnø	16	650	28/1	100	650
Sønder Omme	16	1408	2/1	169	1408
Søndersø		972			
Søllinge pr. Pederstrup	18	2880	21/1	380	2880
Taars	12				
Tranebjerg	18	5835	31/1	515	5835
Tranderup pr. Aerøskøbing	18	4570	31/1	319	4570
Tved pr. Svenborg	16	1193			1193
Tved pr. Svenborg	18	2285			2285
Verninge pr.	15	764	15/1	198	764
Vester Skerninge	18	3297	21/1	566	3297
Total:		10 8032			10,8032

about by single rails fitted behind the blades and which come out when the speed is high enough. In so doing, they spoil the profile of the blades, which has a braking effect. To counteract bending because of wind pressure, the blades are fixedly attached to the boss. They slant somewhat backwards. The effect of this is that whenever the wind speed increases, and so the speed of rotation too, centrifugal force will try to level out the wings until equilibrium is brought about between the bending due to this centrifugal force and bending due to direct wind pressure.

The dynamo is housed up in the mill itself and is driven by the latter's axle via a gear. Much thought was given to making the dynamo approximate the theoretically correct characteristics as much as possible. The installation is also equipped with a stepback relay (corresponding to the La Cour key), overload releases and voltage limiters, as well as a rear wind relay, which acts like a brake and comes into play whenever the wind suddently changes its course and blows from behind.

The dynamo has a power of 50 kW, but with greater wind intensities it turned out possible to load it with a maximum of 70 kW. One of the reasons for the very high efficiency of this motor is that it runs quickly. This design is possible because the blades are streamlined and possess a very small rotation and can therefore be made very small and, as a result, light.

By the "speed of a windmill" is meant the ratio between the speed of the blade tips and the wind. In the case of mills of the sail clapper type, this ratio is about 2.5 and in the case of the aeromotors, which turn at more than 90 rpm, the ratio is about 9. A sail clapper with the same diameter would make only somewhat more than 20 revolutions.

This month (April) a new aeromotor was put into operation by A/S Burmeister & Wain; this is equipped with a 60-kW DC dynamo and generates current for the electricity authority in Rofhaloøen. These two types of wind motors are equipped with iron towers. At the present time, aeromotors with reinforced concrete towers are being erected in many places in Holland and here in Denmark. For the electricity authority in Fredrikshavn, two aeromotors are being built, each with three blades with a span of 24 m. They will generate 70 kW. The Employer's Association was willing to lend its support for these motors by granting an inexpensive loan to the municipality in recognition of the significance of the matter for the national economy.

We can get an idea of the wind intensity and "wind quantity" that can be counted on by looking at Table 2, which shows the annual variations in the wind as measured over a number of years in Copenhagen and Vamdrup. Strictly speaking, figures for these two places cannot be directly compared with each other since the two anemometers were not installed under equally favorable conditions (the one in Copenhagen was up in the crane mast of the military shipyard, while the one in Vamdrup was up on a roof).

If now we consider that a wind motor can work beginning with a wind speed of 5 m/sec and above, we can see that it can work 79% and 67% of the hours of the year in Copenhagen and Vamdrup, respectively.

We have wind-force statistics from Danish lighthouses, too, /4
and when these are compared with the foregoing, it can be seen that the relation for some of the country's lighthouses agrees with the figures given by the Meteorological Institute for Copenhagen, while they are somewhat lower for the other.

If we know the wind speed, on its basis we can determine the effect delivered by the wind motor which, for the rest, increases according to a third degree curve until "sail shortening" takes

TABLE 2. FREQUENCY OF DIFFERENT WIND SPEEDS (m/sec) MEASURED IN COPENHAGEN 1895-1920 AND VAMDRUP 1883-1910

Wind speed m/sec	Copenhagen % of hours of year	Vamdrup % of hours of year
0- 4.9	20.7	33.0
5- 9.9	46.2	55.3
10- 14.9	26.5	10.2
15	6.6	1.5
	100.0	100.-

place. From this point on, the delivered effect is constant. In this manner we get characteristics for wind motors, and if they are now compared with the wind statistics, we can then determine the annual production of the installation. For a 17.5-m aeromotor installed at Copenhagen we get 234,000 kWh per year and for Vamdrup, 130,000 kWh (cf. Table 3).

Favorable conditions for running such a motor can probably be found from smaller rural electricity authorities, where the motor can be erected in the immediate vicinity of the authority, so that it can be served from there and the distribution network thus does not become too long. Assuming that the wind relations are so favorable that we can count on an annual production of 200,000 kWh, we arrive at the production costs shown in Table 4, which range from 3.05 Øre per kWh, depending on whether we calculate with 10% or 40% annual interest and writing-off.

Economic Aspects /5

At the present time, many electric power plants must use 2-kg peat at 5 øre for each kWh; if we count with 2 øre for running costs, then we get a production cost of 12 øre per kWh.

TABLE 3. ATTAINABLE ANNUAL KILOWATT HOURS FOR AN FLS AEROMOTOR 17.5/60 DIRECT CURRENT WHICH SHORTENS SAIL AT A 10-m WIND WITH A WIND FORCE AS MEASURED IN COPENHAGEN ON THE CRANE MAST OF THE MILITARY SHIPYARD AND IN VAMDRUP

		Copenhagen		Vamdrup	
Wind force	kW delivered by the aeromotor	Number of hours per year	kWh production of the aeromotor	Number of hours per year	kWh production of the aeromotor
5 m/sec	0	1815		2932	
5	5.0	731	3 700	1572	7 900
6	12.0	904	10 800	1241	14 900
7	20.0	784	15 700	877	17 500
8	30.5	775	23 600	692	21 100
9	42.5	860	36 600	449	19 100
10	50.0	679	34 000	336	16 800
10	50.0	2212	110.000	661	33 000
		8760	234.400	8760	130 000
		ca. 235 000 at Copenhagen		ca. 130 000 at Vamdrup	

TABLE 4. PRODUCTION COSTS OF THE AEROMOTOR. INSTALLATION COSTS: Kr. 55,000, PRODUCTION: 200,000 kWh

		øre/kWh	øre/kWh	øre/kWh	øre/kWh
Maintenance and service	600 Kr per year	0.3	0.3	0.3	0.3
Interest and writing-off	10%	2.75			
	20%		5.5		
	30%			8.25	
	40%				11.0
Production costs, øre/kWh		3.05	5.8	8.55	11.3

If we consider the connection between the price of electricity and the writing-off of different amounts, the above-mentioned production cost has a good chance of giving the interest and writing-off. With a production of 100,00 kWh, we get more than 20% for interest and writing-off and with 160,000 kWh, we get 33%.

In order to investigate the profitability of electricity generation with wind motors, we calculated Table 5 below. It embraces different electric power plants, and these are divided into three groups:

group I: very large, modern plants;
group II: fairly large and fairly modern plants;
group III: smaller and more or less modern plants.

Calculated for each group is a production cost consisting of fuel costs plus 25% for running costs, and this production cost is recalculated on the basis of "normal" fuel prices as well as on the basis of coal prices at 70 Kr. per ton and 40 Kr. per ton. If we calculate with 25% as running costs, it can be seen that in some places we must reckon with ciphers that are even somewhat lower than fuel costs, while in other places, we must reckon with the full running costs.

The prewar price of windmills amounted to 2/3 of today's price, which must be taken into account.

At prewar prices and 200,000 kWh, an installation of group I will give 5% for interest and writing-off. Group II gives under the same circumstances 13%, i.e., writing-off in 10 years, and group III gives the same 13% with only 160,000 kWh. It can be seen on the basis of the statistics that the price of coal during the 9 years 1918/26 amounted to 72 Kr. per ton, and in the 50 years /6

1918/1932, it amounted on the average to 50.50 Kr. If on this basis we wish to estimate a probable coal price for a certain period in the future, when this war will be over, to fix it at 40 Kr. per ton will probably be on the low side. On this assumption, a plant of group I with only 160,000 kWh will get 7% for interest and writing-off or, in other words, a single windmill mounted in connection with a large and modern plant can be written off in 20 years, and the relation becomes even more favorable when the wind motor can be mounted in a place where direct current is used and where the alternating current generated by the large plant must therefore first be transformed.

A plant of group II has a production cost of 4 øre. A production of 160,000 kWh gives 11% for interest and writing-off, and 200,000 kWh gives 13-1/2% or complete writing-off in 10 years.

If we reckon with the higher coal prices of 70 Kr. per ton, a plant in group III will give 25% with 160,000 kWh and 32% with 200,000 kWh. If, finally, we reckon as before with peat gas, we get 33% with 160,000 kWh and 40% with 200,000 kWh.

In those cases where the wind motor cannot be installed in the electricity plant, we shall have to take into account the distribution network, which can play a role. If we assume that in two different places at some distance from the electricity plant several installations are to be found that are connected to the plant with heavy cables, then we can erect a wind motor in each of these two places and let it act upon the network.

If, on the other hand, circumstances are such that a number of users are located around point 3, but there is no heavy cable from there to the plant, then, so far as this is concerned, we can erect the wind motor wherever we want. But then we will have to bear the costs of a sufficiently heavy cable.

In generating alternating current, it has been found that it is most expedient to let the aeromotor draw a synchronous generator. The figures are somewhat less favorable than for direct current because of the loss in the excitor. On the other hand, to have alternating current generated can be an advantage in many respects.

In the case of larger installations, it would be possible to connect a number of aeromotors to a single collecting center with a joint excitor, and the economic result would then become somewhat, be it ever so little, better.

The national economic side of the question is an essential point. The wind motor means a saving in coal imports into the country. At the present time, mounted or ordered wind motors already mean a saving of 3500 tons of coal per year or, at a coal price of 70 Kr. per ton, a total of 245,000 Kr. per year.

If a smaller plant replaces half of its fuel with wind power, this means that it uses no more imported coal per kWh than a large plant. A medium-sized plant needs to replace only 1/3 of its production with wind power in order to obtain as great a saving in coal as a large plant. In the case of very large plants, /7
it will pay off to erect wind motors at points remote from the network chiefly in places where transformers must already be used.

The results shown in Table 5 below do not quite accurately reflect the results of the aeromotors that have been erected because these motors have only been in operation a comparatively short time. The relatively high performances in kWh are probably correct, but we do not yet have enough experience to decide how much kW can be obtained per year; it will take some time before this can be determined.

The numerical results that are given are therefore not absolutely reliable, but they are given in order to indicate that there is an overwhelming probability that numerical results can be obtained that are really of significance.

The speaker ended his lecture with the following utterance: "Many things come to the fore in a time of crisis such as this, and many things disappear again as our heads rise above the waters in which we have landed, or in which we are in the process of landing, but as sure as it would have been an advantage for our country if we had had many wind-driven electricity plants when things began going downhill, I believe that it is an advantage that interest in the matter now exists and that it will be advantageous if this interest subsists into the future, so that one of our lesser national energy sources can become of even greater use to our country than it has been so far."

TABLE 5. EXTRACT FROM STATISTICAL INFORMATION ABOUT ELECTRICITY PLANTS AVERAGED FOR THE YEARS 1937/38 AND 1938/39

	Annual production in millions of kWh	I Coal at 6000 kg and fuel oil			II Writing-off of machine inventory lubricating oil	III Sum of I + 25% II	IV Sum of I + 25% II expressed in	V Sum of I + 25% II expressed in	VI For a coal price of 70 Kr./t V. 70 Kr/t V.	VII For a coal price of 40 Kr/t
		Kr/t	kg/kWh	Øre/kWh	Øre/kWh	Øre/kWh	kg/day/kWh	kg.coal/kWh	Øre/kWh	Øre/kWh
1 Copenhagen	411.2	Coal 19.1	0.68	1.30	0.32	1.38		0.72		
2 Sønderjylland	36.1	15.65	0.65	1.02	0.14	1.06		0.68		
3 Group I: average of 1 and 2				1.16	0.23	1.22		0.7	4.9	2.8
4 Frederiksberg	32.3	26.80	1.00	2.68	0.39	2.78		1.04		
5 Odense	41.2			2.53	0.45	2.64		0.99		
6 Aarhus	36.7	26.56	0.81	2.15	1.63	2.56		0.97		
7 Aalborg	17.4	26.75	0.92	2.46	1.00	2.71		1.01		
8 Group II: average of 4, 5, 6 and 7				2.46	1.14	2.67		1.0	7.0	4.0
9 Svendborg	5.5	Oil 90.5	0.30	2.69	1.13	2.97	0.33			
10 Thy	1.9	104.00	0.30	3.12	0.95	3.36	0.32			
11 Ringsted	1.3	106.00	0.32	3.39	0.36	3.48	0.33			
12 Skern	0.5	118.00	0.31	3.66	0.60	3.81	0.32			
13 Aerø	0.4	111.50	0.36	4.01	0.85	4.22	0.38			
14 Group III: average of 9, 10, 11, 12 and 13				3.38	0.78	3.57	0.336	Coal 26.70 1.3	9.1	5.2

ANNEX II. Calculation of the Efficiency of the FLS Aeromotor (Diameter: 17.5 m) /1

A quantity of air with a mass m that moves forward with a velocity v can deliver a quantity of work A equal to:

$$A = 1/2\ mv^2 \qquad (\text{kg}\cdot\text{m})$$

The mass is now equal to the weight of the displaced quantity of air divided by the acceleration due to gravity g. The mass that streams through a section F per second is thus:

$$\boxed{\frac{F.v.\gamma}{g} = \rho.F.v \qquad \frac{(\text{kg.sec})}{\text{m}}} \qquad a$$

For a motor, the through-flow surface is $\frac{\pi}{4} D^2$ if D is the real diameter, while the value of the air density ρ at sea level is equal to 1/8 $\text{kg}\cdot\text{sec}^2/\text{m}^4$.

The power (work/sec) that can theoretically be delivered is

$$N_{th} = \tfrac{1}{2}\,\rho.F.v.v^2 = \frac{\pi}{64} D^2\ v^3 \quad \text{kgm/sec} = 0.000482\ D^2.v^3.\text{kW}. \qquad b$$

It can be shown that a mill in the favorable case can deliver:

$$\boxed{N = \frac{16}{27} N_{th} = 0.5926\ N_{th}} \qquad c$$

Now for calculation of the efficiency we have at our disposal the following data:

Wind speed	Delivered power
m/sec	kW
5– 5.9	5
6– 6.9	12
7– 7.9	20
8– 8.9	30.5
9– 9.9	42.5
10–10.9	50

Inasmuch as the wind speed data are 5-5.9, 6-6.9, etc., it is necessary, if we wish to determine the efficiency accurately, to calculate only the average theoretical power of the different speed intervals. This is:

$$N_{th} = \int_{v_1}^{v_2} \frac{0.000482\ D^2 v^3 dv}{v_2 - v_1} = \frac{0.0001205\ D^2\ (v_2^4 - v_1^4)}{v_2 - v_1} =$$

$$= 0.0001205\ (v_2 + v_1)^2\ (v_2 + v_1)\ D^2.$$

Now we calculate the efficiency as follows; /2

V_1	V_2	$(v_1+v_2)(v_1^2+v_2^2)$	D^2	$(v_1+v_2)(v_1^2+v_2^2)D^2$	N_{pr}	$N_{th\,gem}$	V_{gem}	$N_{m\,gem}$	η_{pr} in %	η_{pr} in %
m/sec	m/sec	m^3/sec^3	m^2	m^5/sec^3	kW	kW	m/sec	kW	of $N_{th\,gem}$	of $N_{m\,gem}$
5	5.9	651.929	306,25	199650	5	24.06	5.46	14.28	20.8	35.1
6	6.9	1078.569		330310	12	39.60	6.46	23.53	30.2	51.0
7	7.9	1660.009		508375	20	61.23	7.46	33.30	32.6	55.0
8	8.9	2420.249		741200	30,5	89.31	8.46	52.52	34,2	57,8
9	9.9	3383.289		1036130	42,5	124.35	9.46	74.04	34,1	57,6
10	10.9	4573.129	306.25	1400520	50	168.76	10.46	100.00	29,6	50

If we plot the values of column 10 in a graph (Fig. 5), then it turns out that the efficiency reaches a maximum of 34.5% for a wind speed of 9 m/sec.

/3

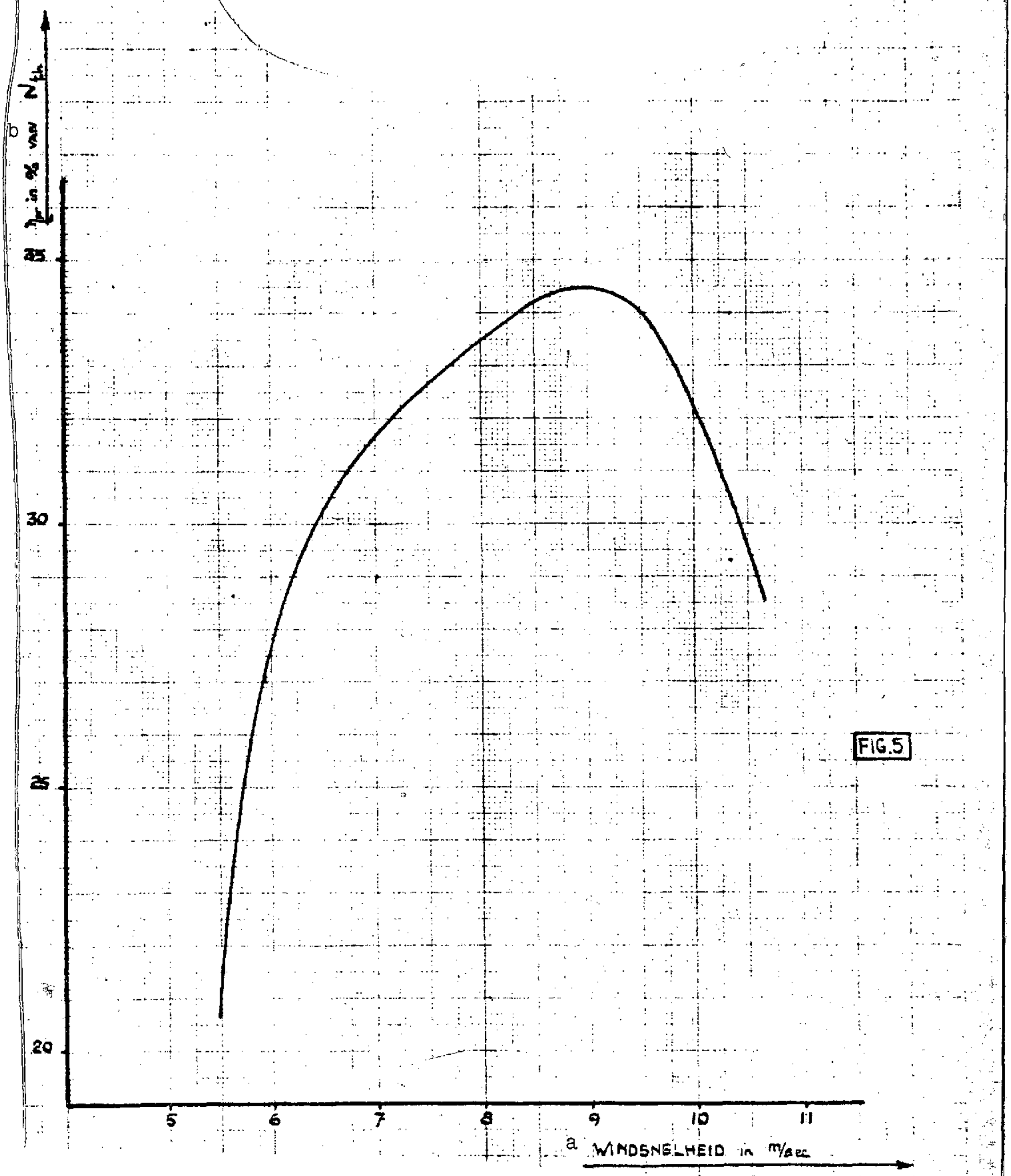


Fig. 5. Efficiency curve for the FLS aeromotor for different wind speeds (wheel diameter: 17.5 m).

Key: a. Wind speed in m/sec; b. of

ANNEX III. Synopsis of the Improvement that Mills in the Netherlands as well as Abroad Have Undergone Over the Years /1

In the Netherlands

In the last few decades, the old Dutch mills have had to wage a hard fight against more modern energy sources that have come into use, such as electric motors and Diesel and suction gas engines. That many mills have nevertheless managed to survive the fight is largely due to the many persons and authorities that have worked on improving and modernizing them (among others "de Hollandse Molen" [The Dutch Mill], a society for the preservation of mills in Holland).

Well-known improvements are the so-called Dekker sail and van Bussel sail. In 1935 the Prince Mill Committee was set up to modernize the Prince mills located in the Schiebroek polders, and it was expected that the experience acquired with the Prinse mills could be turned to good account in the case of other Dutch mills. The result was a considerable improvement. But it should be borne in mind that the Committee was not supposed to bring about any radical improvements inasmuch as it had undertaken to affect the "pure Dutch character" of the mills as little as possible.

Abroad

In Germany, it was especially Major K. Bilau who considerably improved windmills by giving a new shape to their sails. He is also the author of the well-known book Windmühlen bau einst und jetzt [Windmill Construction Then and Now]. His compatriot Honnef is known for the enormous so-called Honnef project, with which he hoped to liberate vast quantities of energy from the wind by erecting an enormous mill at a very great altitude.

In Russia, much research has been done in the framework of the well-known 5-Year Plans to exploit wind power profitably. Here many mills and wind-driven power stations were erected. A well-known project is the Syur mill, with which an efficiency of about 25% was reached. Inasmuch as the Russians maintain great secrecy in all areas, however, little is known about the results achieved and the experience acquired.

In Denmark, it was especially Prof. La Cour who did much to improve windmills (so-called "sail clappers"). He was the first to bring about a turning point in windmill construction and to conduct wind tunnel experiments with mills. In Askov, with state help, he created an institute for mill research.

After Prof. La Cour it was Dr. Povl Vinding who improved mills and became known for his so-called Agrico mill.

In 1940, at the initiative of Gunnar Larson, the so-called FLS aeromotor was built, which signified a considerable improvement and had a maximum efficiency of about 34.5% (see Annexes I and II).

ANNEX IV. Copy of a Letter from the Royal Dutch Meteorological Institute to Mr. E.A. Driessen, Scientific Bureau of KLM, Schiphol /1

Royal Dutch Meteorological Institute

De Bilt, August 2, 1948
Telephone No. 28041
P.O. Box No. 4465

No. 5771/III/D/R.
SUBJECT: Wind frequencies
Acknowledgement of your letter of
July 17, 1948, No. GCV 380/Dr/MS.

Enclosures: back/new 1

In answer to your above-cited letter, I am sending you a synopsis of wind frequencies in $^{o}/oo$ at Den Helder and Vlissingen averaged over the year for an altitude of 6 m above level ground.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Den Helder	8	68	97	111	117	111	102	89	71	61	48	38	27	18	13
Vlissingen	12	58	131	140	148	122	104	84	60	46	31	21	14	10	7

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Den Helder	8	5	3	2	1	0.7	0.4	0.3	0.1	0.02	0.02	0.00	0.01	0.00	0.00
Vlissingen	5	3	2	1	0.6	0.3	0.2	0.1	0.05	0.02	0.01	0.01	0.01	0.00	0.00

The speed classes 1, 2, etc. correspond to the intervals 0-0.9, 1.0-1.9 m/sec, etc.

In converting from the wind speed at an altitude of 6 m to an altitude of 50 m, the following allowances that we have extrapolated must be applied to the wind speed:

Wind speed, m/sec	0-2	3	4	6	8	10	12	14	16	18	20	22 and higher
% allowance	32	31	29	27	26	25	23	22	21	20	19	

For the Manager in Chief

The director of the Climatology Department

Dr. L.J.L. Dey

To Mr. E.A. Driessen
Scientific Bureau of the KLM
Schiphol

1. FLS Aeromotor

1.1. As has already been mentioned in Section 4.2 of the present report, it appears from Mr. Lulofs' discussion (Annex VI) that during the first 20 years current will have to be delivered at a price of 1.4 ct/kWh and during the following years, at 0.5 ct/kWh, if the total writing-off time amounts to 50 years. Hence it follows that when the maintenance costs amount to 0.25 ct/kWh, during the last 30 years an amount of 0.25 ct/kWh is available for interest and writing-off.

Thus, over the 30 years the following amount can be written off:

$$\frac{0.25 \times 2200{,}000}{5.437133} = \text{f. } 10{,}000$$

in which 5.437133 is the percentage of interest and writing-off and 220,000 is the number of kWh that is produced yearly by the plant. The interest on this amount per year and per kWh at a rate of interest of 3.5% is:

$$\frac{0.035 \times 1{,}010{,}000}{220{,}000} = 0.16 \text{ ct.}$$

Thus, available during the first 20 years for interest and writing-off is the selling price (1.4 ct/kWh) reduced by the maintenance costs (0.25 ct/kWh) and the interest (0.16 ct/kWh) on the amount that is written off in the last 30 years.

Thus, at 7.036108% interest and writing-off, the maximum initial expense can amount to

$$f\ 10{,}100 + \frac{(1.4 - 0.25 - 0.16)\ 220{,}000}{7.036108} =$$

$$f.\ 10{,}100 + f.\ 31{,}000 = f.\ 41{,}100,$$

i.e. f. 821 per installed kW.

1.2. If we write off the FLS aeromotor normally in 50 years and again assume that the installed power is 105% of the usable power, then we get the following figures:

Period of interest and writing-off in years	Interest and writing-off	Maintenance and service 2.69 x f 200- per year	Total production cost	Total production costs when the installed power is 105% of the usable power	
50	0,71	0,25	0,96	1,01	ct/kWh.
40	0,78	↑	1,03	1,08	"
30	0,91	│	1,16	1,21	"
20	1,17	│	1,42	1,49	"
15	1.44	│	1,69	1.78	"
10	2.00	│	2,25	2,38	"
7	2.72	│	2,97	3,12	"
5	3,69	│	3,94	4,13	"
2	8,76	↓	9,01	9,46	"
1	17,22	0,25	17.47	15,34	"

2. Wind Power Plant with a Wheel Diameter of 50 m

/2

2.1. In the same manner as in Section 1.1, we can also calculate the initial expense for a large wind power plant that "shortens sail" at 10 m/sec. Again available for interest and writing-off for the last 30 years is 0.25 ct/kWh.

Thus, the amount that can be written off over this period is:

$$\frac{0.25 \times 1\ 900\ 000}{5.437133} = f.\ 87\ 500.--$$

Here 5.437133 is again the percentage of interest and writing-off and 1,900,000 is the annual production of the plant in kWh.

The interest on this amount per year and per kWh at a rate of interest of 3.5% is

$$\frac{0.35 \times 8\ 750\ 000}{1\ 900\ 000} = 0{,}16 \text{ ct.}$$

Now we can determine the maximum initial expense in the same manner as in Section 1.1. This is:

$$\text{f. } 87\ 500,\text{--} + \frac{(1.4 - 0.25 - 0.16)\ 1\ 900\ 000}{7{,}036108} =$$

$$\text{f. } 87\ 500,\text{--} + \text{f. } 267\ 500,\text{--} = \text{f. } 355\ 000,\text{--}$$

i.e. f. 835 per installed kW.

2.2. Owing to the increased production of a plant that "shortens sail" not before 15 m/sec, at the same maintenance costs during the last 30 years the following extra amount can be written off:

$$\frac{0.25 \times 1\ 500\ 000}{5{,}437133} = \text{f. } 69\ 000,\text{--}$$

Here, 1,500,000 is the increase in production in kWh because of increased "sail shortening" and 5.437133 is the percentage of interest and writing-off. The interest on this amount per year and per kWh is

$$\frac{0.035 \times 6\ 900\ 000}{1\ 500\ 000} = 0{,}16 \text{ ct.}$$

A price of 1.4 ct/kWh for this extra production cannot be maintained inasmuch as its commercial value is less. For this increase in production only 1.1 ct/kWh can be taken into calculation (see Annex VI), so that the increase in the initial expense because of the strengthening of the plant could therefore amount at most to

$$f.\ 69\ 000.-- + \frac{(1.1 - 0.25 - 0.16)\ 1\ 500\ 000}{7.036108} =$$

$$f.\ 69\ 000.-- + f.\ 147\ 000.-- = f.\ 206\ 000.--$$

i.e. about 57% of the original initial expense.

2.3. As has already been said in the present report, in the case of normal writing-off, for a plant that "shortens sail" at 10 m/sec we must start from an initial expense of f. 311,000, and for a plant that "shortens sail" not before 15 m/sec, an initial expense of f. 470,000 (assuming that the strengthening of the plant costs 50% of the original initial expense.

a. For a large plant that "shortens sail" at 10 m/sec /3

Period of interest and writing-off in years	Interest and writing-off	Maintenance and service	Total production cost	Total production cost when the installed power is 105% of the usable power	
50	0.70	0.25	0.95	1.00	ct/kWh
40	0.77		1.02	1.07	"
30	0.89		1.14	1.20	"
20	1.15		1.40	1.47	"
15	1.42		1.67	1.76	"
10	1.97		2.22	2.33	"
7	2.68		2.93	3.07	"
5	3.63		3.88	4.07	"
2	8.62		8.87	9.31	"
1	16.94	0.25	17.19	18.06	"

b. For a plant that "shortens sail" at 15 m/sec

Period of interest and writing-off in years	Interest and writing-off	Maintenance and service	Total production cost	Total production cost when the installed power is 105% of the usable power	
50	0,59	0,25	0,84	0.88	ct/kWh
40	0,65		0,90	0,94	"
30	0,75		1,00	1,05	"
20	0,97		1,22	1,30	"
15	1,20		1,45	1,52	"
10	1,66		1,91	2,01	"
7	2,26		2,51	2,64	"
5	3,06		3,31	3,48	"
2	7,28		7,53	7,90	"
1	14,31	0,25	14,56	15,29	"

ANNEX VI. Economics of Using Wind Power for Electricity Supply in the Netherlands

W. Lulofs

Available for the calculation of profitability are data from a lecture that Mr. O.V. Mørch delivered to the Danish Engineers' Association on April 23, 1941, in which he converts the results obtained with a trial aeromotor erected in Aalborg to the case of a similar installation intended for Copenhagen.

The calculation shows that for the case of this installation, the so-called FLS aeromotor with a wheel diameter of 17.5 m, 50 kW can be developed with an annual production of 234,000 kWh, if automatic "sail shortening" comes into operation at a wind speed of 10 m/sec and productive power is kept constant. The prewar installation costs amounted to f. 13,600, and the service and maintenance costs, 0.091 ct per excited kWh.

On the basis of these figures a calculation is carried out for such an aeromotor to be installed in den Helder at an altitude, if erected on dune or dike, more or less corresponding to that of the Danish motor.

For a power of 50 kW, this calculation yields an annual production of 220,000 kWh and is thus in good agreement with the Danish relations.

Where no fast line can be traced out for the course of the future money values in which initial expenses, wages, etc. are to be expressed, it is assumed for calculating the profitability that these values will be 2.69 times that of the prewar prices.

Let us first calculate what costs will be connected with future electricity generation by means of steam power plants, which is usual here in Holland, in order to determine on this basis what value electricity from the wind will have for it, with the idea in mind that the latter will in the first place have a share in the increase, which promises to be very considerable.

Any new plant to be built will be intended to take care of the land tax as much as possible and, assuming that the plants will ultimately here in Holland, too, be coupled and operate in a coupling relation, they would theoretically be able to operate at full capacity 8760 hours of the year. But boilers must be cleaned after a certain time and must be shut down every other year for inspection, steam turbines must be overhauled, components of the installation must be shut down for repairs.

If we now calculate that 20% of the installed power will for these reasons not be forthcoming, which is a low figure, then the number of operating hours of the installed power per year comes to 7000.

The initial expenses for a large plant with 30,000 kWh turbines and corresponding boilers amounted per kW of installed power on the average to f. 115 before the war, so that for future relations we must reckon with 2.69 x f. 115, or f. 310.

With a rate of interest of 3-1/2% and an economic life of 20 years, we must reckon for similar annuities with 3-1/2 + /2
+ 3.536% = 7.036% for interest and writing-off per year. (This writing-off percentage was globally fixed inasmuch as there is no writing-off for grounds; but a writing-off duration of 20 years was taken into account.)

The capital costs per kW per year thus amount to 7.036% of f. 310 = f. 21.8, so that the capital expenses for the generated 7000 kWh per year per kWh amount to 0.31 ct.

Before the war, maintenance costs per kWh, including service, amounted to about 0.15 ct; thus, here we must reckon with 2.69 x 0.15 ct, which is 0.405 ct per kWh.

If coal costs are fixed at f. 25 per ton for a caloric value of 6800 cal/kg and the average efficiency of the plant is assumed to be 26%, then per generated kWh, 3300 cal or 0.485 kg coal with a cost of 1.25 ct per generated kWh will be necessary.

Thus, the total costs are:

Capital	0.312 ct per kWh
Maintenance and service	0.405 " " "
Fuel costs	1.21 " " "
Total	1.927 or approximately 2 ct per kWh[2]

Now wind power will take over in the first place the kWh that must be generated with a productive power of the lowest efficiency.

If we now assume that in the first 20 years that steam productive power is taken over, the average coal figure will be that of present-day production, then we certainly get no flattering picture.

These figures were as follows:

1947	1946	1939
0.559 kg per kWH	0.568 kg per kWh	0.548 kg per kWh

so that a figure of 0.55 kg per kWh becomes reasonable.

[2] This calculation of costs is on the low side; for the USA, production costs per kWh for 100-MW plants is calculated to be 2 ct. and for the Netherlands, 2.4 ct.

Thus, per wind-generated kWh 0.55 x 2.5 ct or 1.375 ct will be saved in fuel costs.

Owing to the uncertain nature of wind power delivery, there will be no important savings in service, but there will be in maintenance; if we fix the saving at half, this comes to 0.2 ct per kWh, while for the above-mentioned reasons, no saving in capital expenses is taken into account.

Thus, we can reckon with a saving of 1.375 + 0.2 ct = = 1.575 ct per delivered wind power kWh. If we now reckon that in the first 20 years the kWh must be delivered against an 11% reduction, then we can reckon with a possible receipt of 1.4 ct per kWh during this period, while under the circumstances we have been sketching, all the wind-generated kWh can be turned to account.

And now as far as the production costs of the wind power plant is concerned:

We can safely assume that the wind power plant will have a service life of 50 years, which means the same economic life. The chief mechanical components are the generator whose efficiency, depending on the size, amounts to 93-97-1/2%, while the wind motor can be reckoned at 35%, as against a theoretical possible maximum efficiency of 59.26%. The possibility of a practically important increase in the economy of the wind power plant is thus thinkable only by increasing the economy of the sail design as the result of a possible future deepening of our understanding of aerodynamics. But these modifications will not entail too great a cost.

For the FLS aeromotor that will be built in den Helder, the production figures are 50 kW and 220,000 kWh out of a working duration of 4400 hours per year. /3

If we assume that in the second period, i.e., the last 30 years, it will be possible to find use for the generated electric energy at 0.5 ct per kWh, while the service and maintenance costs will amount to 0.25 ct, then per kW of useful power 4400 x 0.5 ct or f. 11 will be available for interest and writing-off per year.

Per f. 100 book value, at a rate of interest of 3.5% and writing-off over 30 years, 3.5% + 1.937 or 5.437 is necessary per year for interest and writing-off (same annuity).

At the beginning of this period, the book value may amount to 11/5.437 x f. 100, i.e., f. 203.

Left over for interest and writing-off per kW in the first period of 20 years is 4400 x 1.15 ct = f. 50.70 per year.

Out of this we must defray the interest of f. 203 that is not written off in the first period; at 3.5% this amounts to f. 7.11, and thus there are f. 50.70 - f. 7.11 = f. 43.59 left over for interest and writing-off of the capital that must be paid off in the first period. Thus, this capital amounts to f. 43.59/7.036 x f. 100, i.e., f. 620. Thus, it follows that per usable kW a capital of f. 203 + 620 = f. 823 is justified. If now we reckon that for every 20 mills an extra one must be on hand and will be out of operation for overhauling or repairs, then the installed power is 106% of the usable power, and the installed power per kW may not cost more than f. 784.

Inasmuch as the FLS aeromotor per installed kW costs:

$$\boxed{\frac{\text{f. } 15500 \times 2.89}{60} = \text{f. } 730}$$

there is still a large margin available, and profitability is thus ensured.

According to the calculation, the installation will not pay only if in the first period of 20 years no use is found for the generated kWh at the following minimum prices. The usable kW of the FLS installation has an initial expense of f. 730 x 1.05 = = f. 767.5. Of this, f. 203 may not be written off in the first period of 20 years, so that in these years 5.645 x 7.036 + + f. 7.11 per year, i.e., f. 46.81 in capital expenses must be raised. For 4400 kWh this gives 1.063 ct per kWh, to which another 0.25 ct must be added for service and maintenance, giving a total of 1.313 ct, in which case the installation would not be profitable in the first 20 years.

Even if for unexpected reasons it should be difficult for electricity supply to work together with wind power production on the basis of the above-mentioned prices, it should be clear that at these prices it will be possible to find a use for certain applications, such as electrochemistry or extension of polder draining. Especially does the latter gain in significance now that the plans for the Southern Zuider Zee polders are probably going to be carried out. I will return to this point in greater detail.

The above reflections should make it clear that already out of economic considerations alone the use of wind power on a large scale is justified. We should proceed with building a pilot plant; the results obtained with it will yield valuable data about the possibility of application on a larger scale, keeping our eye on further advantages of using wind power apart from directly economic ones.

Now a 50-kW installation with an annual production of 220,000 kWh is of no practical significance for a country with an electricity requirement of 950,000 kW maximum load and an annual /4 consumption of 3.6 billion kWh, as was the case in 1947, and which figures can be estimated for the current year to be about

1,500,000 kW and 4 billion kWh; in other words, the country would have to be seeded with dozens of such installations in order for them to be of practical significance.

That is why Mr. Driessen has striven to increase the power of such installations by using higher wind speeds.

In this connection he suggests "shortening sail" only at a wind speed of 15 m/sec in consideration of the fact that where production is theoretically proportional to the third power of the wind speed, much greater quantities of energy can be drawn from powerful winds, however short their duration may be.

This is shown by the figures he calculated for a wind power plant with a productive power of 421.75 kW at a wind speed of 10 m/sec, which could develop a power of 1423.42 kW at a wind speed of 15 m/sec, while its annual production in this case would rise from 1,900,000 kWh to 3,400,000 kWh.

Although shifting the "sail shortening" in this manner seems attractive, the consequences that it entails cannot be left unmentioned. In the first place, I would like to point out that it would be more difficult to find a use for the extra results in kWh that would be obtained in this manner, and these results would be of less value, as will be clear from the following consideration.

The wind power plant with a wheel diameter of 15 m that is planned for den Helder would produce 1,500,000 kWh per year more for "sail shortening" at a wind speed of 15 m/sec than for "sail shortening" at a wind speed of 10 m/sec, while the productive power would be increased by about 1000 kW.

Thus, these additionally produced kWh have only 1500 service hours out of the maximum per year and can therefore not be brought into action for 1.4 ct per kWh for the first period of 20 years.

Moreover, because of the very irregular nature of this production, this price cannot be fixed higher than 90% of the fuel costs of normal production, i.e., about 1.1 ct per kWh.

Applying the same calculation as the preceding shows that at the end of the 20-year period, f. 69 per kW cannot be written off, while in this period an amount of f. 147 per kW can be paid off, so that the usable kW of this extra productive power may not come above the installation costs of f. 206 per kW.

But as soon as international coupling of electricity production has come into being, the generation of electricity by means of wind power can constitute an important supplement to foreign water power plants if for no other reason than the fact that the times of maximal production differ in principle for the two. Wind power is considerably greater in the winter as against available water power, which is greatest precisely in the summer, while water reservoirs can serve as buffers to the inconstancy of wind power. While the annual production of water power plants varies sharply, depending on the rain or snowfall during that year, wind power is not subject to great fluctuations in the course of the year.

Here, too, I have maintained my mode of calculation, which is only partially adopted in the report, because this has the advantage that the calculation of capital and exploitation is handled at the same time, whereby as complete an insight as possible is obtained about the factors that determine cost relations.

Whether this extra increase in production, which justifies such a relatively smaller outlay of capital, will nevertheless be justified depends in the first place on the question whether this increase in power is to be paid with the allowable amount of f. 206,000 for the extra 1000 kW, which does not seem impossible, while in any case the important advantage is obtained that this extra production pretty much benefits rural fuel requirements. /5

I do not have sufficient command of aerodynamics to dare express a judgment about the question whether it will be possible to maintain an average efficiency of 35% incident to greater wind speeds between 10 and 15 m/sec by adjusting the sail, etc.; nor about the consequences that the concomitant greater material burden will have and to what extent it will be possible to keep variations in revolutions within reasonable limits, which is so important for electricity generation; but I imagine that the following train of thought may deserve consideration: not to bring about "sail shortening" above a wind speed of 10 m/sec by spoiling the aerodynamic efficiency, as is the case for the FLS aeromotor; but to limit the wind speed for the main aeromotor in principle to 10 m/sec by connecting a second set of sails that stands still up to 10 m/sec with the sails in parallel to the wind direction, but which comes into operation at higher wind speeds by adjustment of the sails and, turning in the opposite direction, draws off the surplus wind speed at the instigation of a second dynamo, which is connected in parallel to the first.

Should this thought be aerodynamically feasible, it can be expected that practice will show that incident to the coming into operation of the second aeromotor, the wind speed should be distributed in a certain ratio between the two sets of wheels, with concomitant dimensioning of the two generators.

Of the three kinds of electricity generation, namely, by synchronous generators, asynchronous dynamos or DC dynamos, for the time being I am inclined to prefer the last in order to convert in a transformer station the coupled production of as great a number of aeromotors as possible to rotary current of constant frequency and voltage. It would lead me too far afield to enter into greater detail.

The above considerations are based on the idea that the generated electricity will not be used primarily but will be utilized in its entirety for rural electricity supply, which entails, as has already been mentioned, that no compensation for kW costs is to be expected because of the uncertainty whether power can always be made available during times of maximum load.

In this respect the economic efficiency of the wind power plant would be advantageous, if a direct use could partly be found for the generated electricity.

Here I have in mind especially the draining of the Southern Zuider Zee polders which, during the limited peak hours that the year contains, could probably remain without draining in the event that the wind power during time of service should be partially insufficient. For such a use, the current prices as calculated above could be increased with a certain share in the capital expenses.

The slight disadvantage that during a limited number of days per year and hours per day it will not be possible to work with electric pumping is in my opinion more than neutralized by the extra certainty of this kind of current delivery in other respects as a result of its being independent of social unrest, war, fuel availability, etc.

Here again it should be pointed out that because of the low prices of current it will be possible to establish new industries, such as electrochemistry, which will be able to use electricity generated by the wind and which, if necessary, could interrupt their collection of current for some hours per day in the peak season.

Finally, it should be recalled that it is precisely in the winter, i.e., during the peak season, that the wind strength on the average is highest, so that production, which is proportional to the third power of the wind speed, is highest precisely at these times in spite of the fact that the mass of the air increases with decreasing temperature. /6

I hope the foregoing considerations will be conducive to giving serious consideration to the problem of using wind power for large-scale electricity production and so the study of this has not yet been taken up by a committee of experts in order to contribute to setting up such a committee.

ANNEX VII. Some Remarks in Connection with the Book, Power from the Wind, by Palmer C. Putnam (1948). /1

The above-mentioned book describes a wind turbine with a wheel diameter of 53.3 m erected on a 2000-ft-high mountain, Grandpa's Knob, in the mountains of central Vermont, USA (Smith-Putnam wind turbine project) with which tests were conducted and experience acquired in 1940-1945. This book makes a number of important points.

1. Performances

In general, the performances of this plant seem to agree with those of the project discussed in our report. But this American wind turbine has in our opinion some important aerodynamic disadvantages as compared with the plant we have been considering.

In the American plant the tower stands in front of the sails, so that the flow is disturbed before it reaches the sails. Moreover, the tower is of an open steel design, so that this, too, has an unfavorable influence on the flow. Inspite of this, this plant achieved a maximum efficiency of 35%.

2.

It also appeared from the book that some safety factors are included in the calculation of power in our report:

a. Safety Factor Through Cubic Factor

The third power of the average of a number of terms is smaller than the average of the separate terms to the third power. The course of wind speed with time is subject to continuous fluctuation. The delivered power depends on the third power of the speed and since in our report an average wind is reckoned with, the found power is therefore really higher. According to Putnam, this difference in power can be as much as 6-8%.

b. Safety Factor Because of Variation in Air Density

In winter the air has a greater density than in summer; wind speeds, too, are on the average higher in winter than in summer. As a result, the powers calculated in our report are somewhat too pessimistic inasmuch as we reckoned with an air density averaged over the year.

3. Reasons Why Research on the Smith-Putnam Wind Turbine Was Discontinued in America

The Central Vermont Public Service Corporation, which paid the costs for the research on and construction of the experimental turbine, was a private company, and in 1945 the shareholders were not ready to invest more money in the project. For one thing, the company set as the outer limit a writing-off percentage of 12%. Putnam himself points out in his book that if the government took wind turbine research and exploitation in hand, the writing-off percentage could be much lower and production costs could therefore drop and the wind turbines could certainly be run profitably.

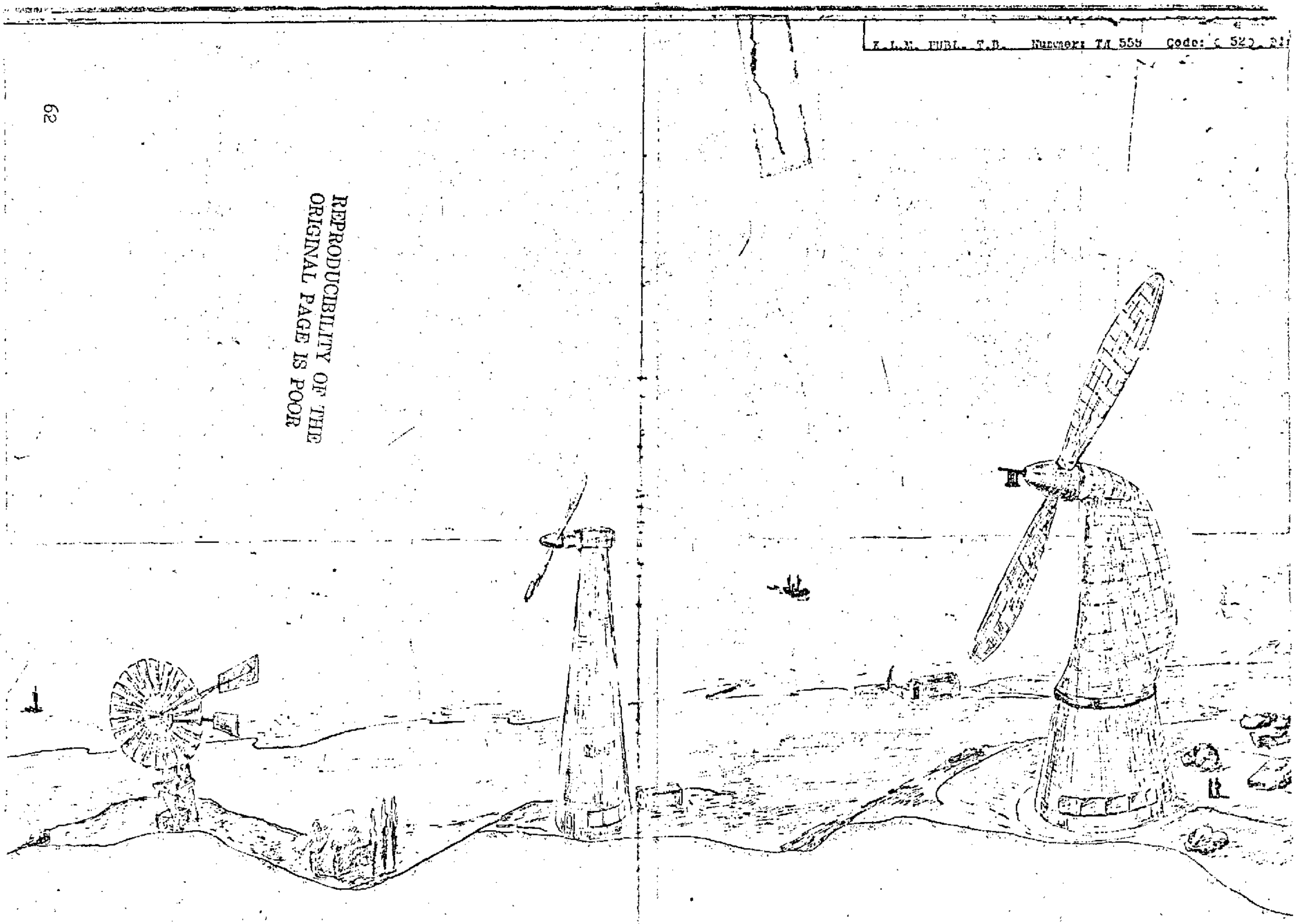
4. /2

The research and construction costs of the Smith-Putnam wind turbine project came to 1 million dollars in 1945. These costs could be significantly less in our country for the following reasons:

a. The special meteorological, geological and biological studies that were necessary in the American research in order to be able to determine somewhat accurately the wind's behavior in mountainous country, too, accounted for a good deal of the costs. These studies are less necessary in the Netherlands inasmuch as we have at our disposal good meteorological data.

b. We can take advantage of the experience acquired in Denmark and America.

c. The cost of labor in Holland is considerably cheaper than in America.



American windmill

Fig. 6

FL5 - AEROMOTOR
Wheel diameter: 17.5 m

Wind power plant
Wheel diameter: 50 m
KLM proposal